

Precision Drell-Yan at the LHC



Uta Klein

University of Liverpool

and

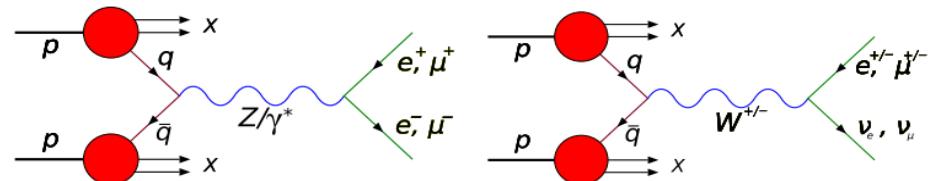
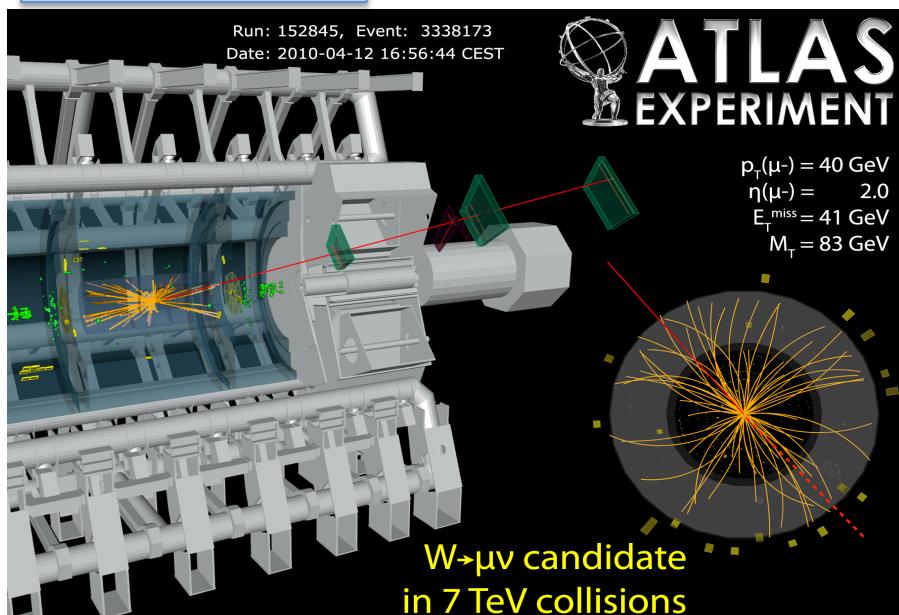
CERN-RFBR-Scientific-Cooperation 12-02-91526-CERN_a

PPSC20: PRECISION MODELLING OF HADRON STRUCTURE AT HIGHEST ENERGIES

Snowmass Energy Frontier Workshop, 4.4.2013

W and Z candidates

$W \rightarrow \mu \nu$



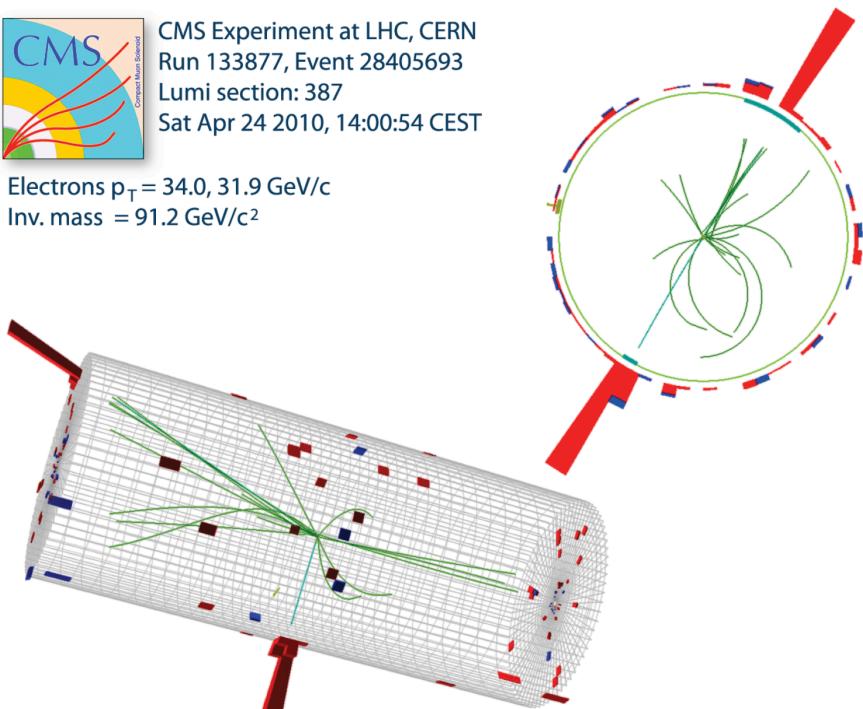
$Z/\gamma^* \rightarrow ee$

Run number: 133877 Event number: 28405693 , Lumi Section : 387



CMS Experiment at LHC, CERN
Run 133877, Event 28405693
Lumi section: 387
Sat Apr 24 2010, 14:00:54 CEST

Electrons $p_T = 34.0, 31.9 \text{ GeV}/c$
Inv. mass = $91.2 \text{ GeV}/c^2$



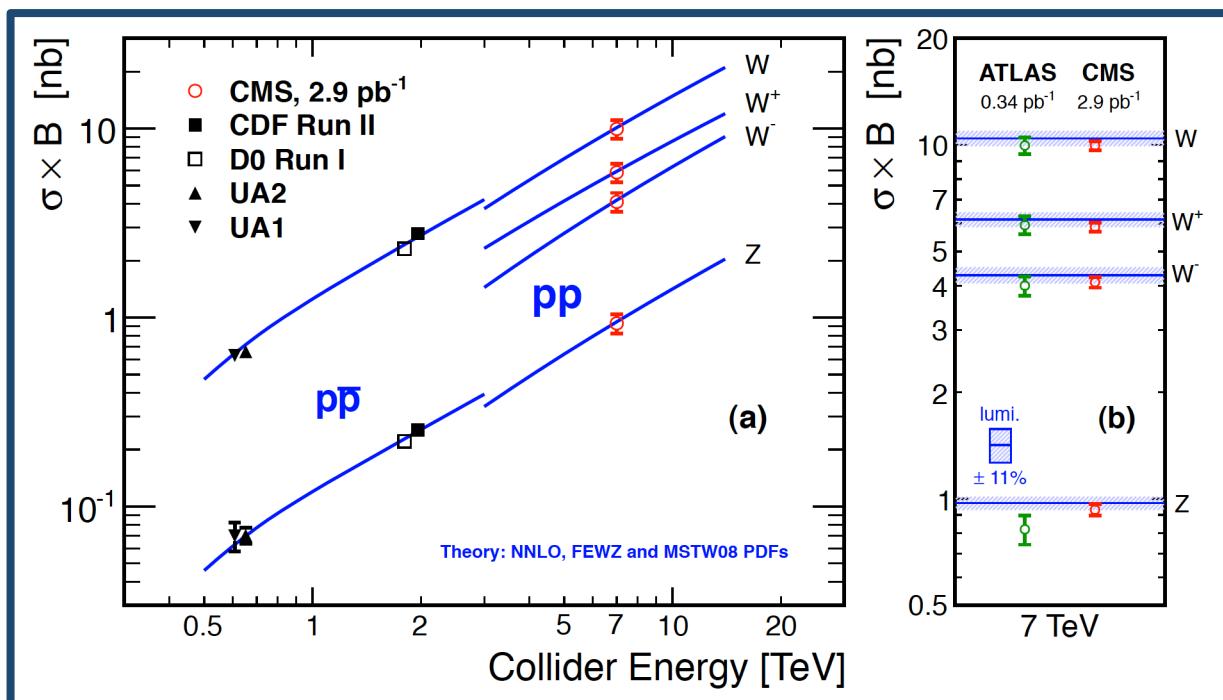
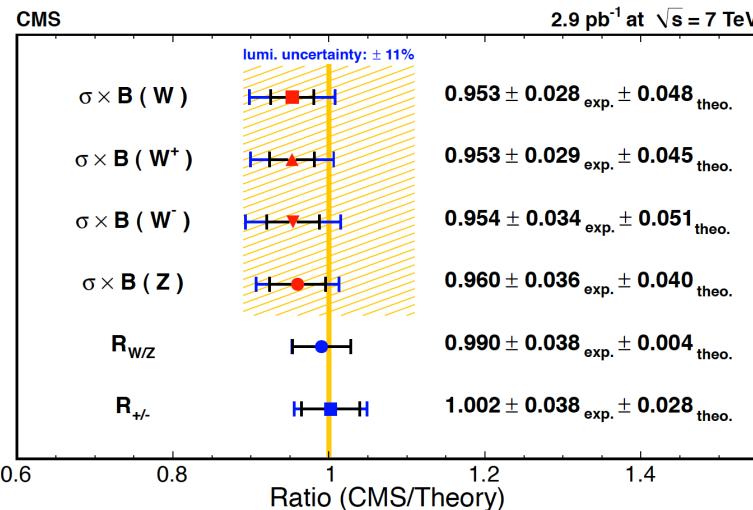
**Clear signature, copious production:
about 10^7 W^\pm and 10^6 Z candidates ($e+\mu$)
per 1fb^{-1} luminosity**

The beginning...

ATLAS and CMS uncertainty
was **11% due to luminosity!**

W/o lumi, e.g. CMS exp.
uncertainties were

- $\delta\sigma(W)$: 2.9%
- $\delta\sigma(Z)$: 3.9%
- $\delta\sigma(W)/\sigma(Z)$: 3.8%



W, Z publications (electron and muon channel)

2010 @ 7 TeV : 0.04 fb⁻¹ delivered (full statistics)

- ❖ CMS :
 - W lepton charge asymmetry JHEP04(2011)050
 - W, Z differential cross sections JHEP10(2011)007
 - Z rapidity and transverse momentum Phys. Rev. D 85 (2012) 032002
- ❖ ATLAS :
 - W charge asymmetry (muon) Phys.Lett. B701 (2011) 31-49
 - ptZ Phys.Lett. B705 (2011) 415
 - W and Z total and diff. cross sections Phys. Rev. D85 (2012) 072004
 - Strange quark density Phys.Rev.Lett. 109 (2012) 012001
 - ptW Phys.Rev. D85 (2012) 012005
 - W polarisation Eur. Phys. J. C72 (2012) 2001
- ❖ LHCb : W and Z in muon channel, JHEP Vol. 2012, Number 6 (2012) 58

2011 @ 7 TeV : 6 (1.1) fb⁻¹ delivered

- ❖ CMS :
 - Drell Yan weak mixing angle (1.1 fb⁻¹) Phys. Rev. D 84 (2011) 112002
 - Forward-backward asymmetry (5 fb⁻¹) Phys. Lett. B 718 (2013) 752
- ❖ ATLAS : phi* in e and mu channel (4.6 fb⁻¹) Phys. Lett. B 720 (2013) 32
- ❖ LHCb : Z → ee (0.94 fb⁻¹) JHEP **02** (2013) 106

W, Z ongoing efforts

→ e.g. overlay plots (for illustration of level of agreement, needs small extrapolations)

- Examples of cuts (2010) W-lepton asymmetry, W cross section vs η

		p_T [GeV/c]	M^T, E_T^{miss}
ATLAS	$ \eta < 2.5$	20	>40, >25
CMS	$ \eta < 2.5$	25,30	
LHCb	$2 < \eta < 4.5$	20, 25, 30	

LHCb can measure for $p_T > 20, 25, 30$ GeV/c; allows to check the extrapolation in p_T

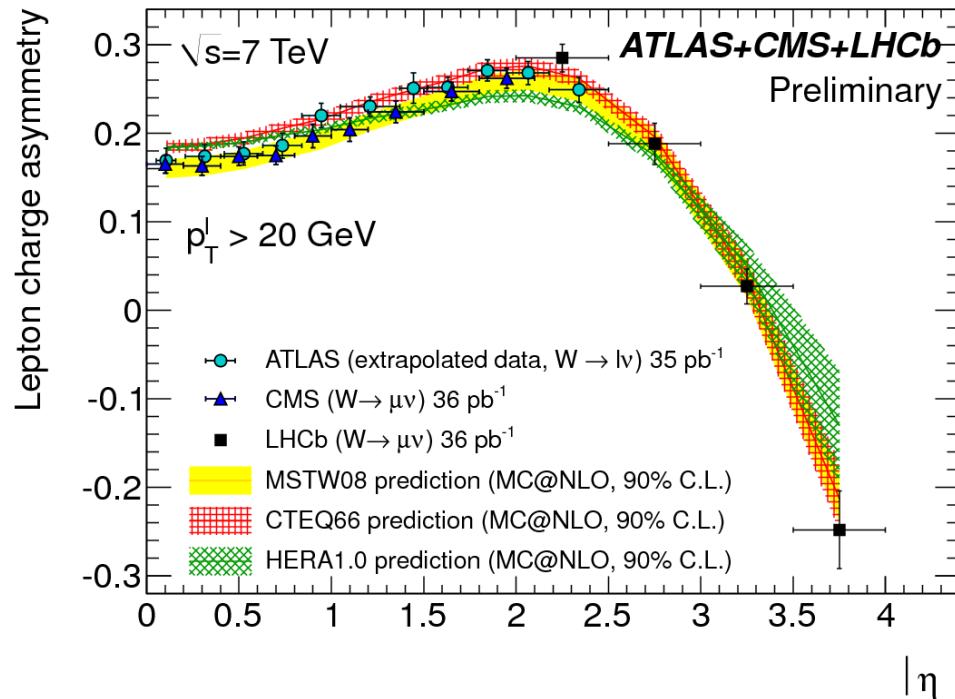
→ historically and detector related different cuts
 Z/ γ^* peak region:

ATLAS: $66 < M_{\parallel} < 116$ GeV/c 2

CMS/LHCb: $60 < M_{\parallel} < 120$ GeV/c 2

LHCb: muons $2 < \eta < 4.5$

→ comparisons rely on the well understood and documented theory calculations



Example : Systematic uncertainties [%]

2010 40 pb⁻¹ : 1-2% precise common fiducial cross sections +3.4% from luminosity. Data averaged taking into account for correlations.

electron	$\delta\sigma_{W^\pm}$	$\delta\sigma_{W^+}$	$\delta\sigma_{W^-}$	$\delta\sigma_Z$
	0.4	0.4	0.4	<0.1
Electron reconstruction	0.8	0.8	0.8	1.6
Electron identification	0.9	0.8	1.1	1.8
Electron isolation	0.3	0.3	0.3	—
Electron energy scale and resolution	0.5	0.5	0.5	0.2
Non-operational LAr channels	0.4	0.4	0.4	0.8
Charge misidentification	0.0	0.1	0.1	0.6
QCD background	0.4	0.4	0.4	0.7
Electroweak+ $t\bar{t}$ background	0.2	0.2	0.2	<0.1
E_T^{miss} scale and resolution	0.8	0.7	1.0	—
Pile-up modeling	0.3	0.3	0.3	0.3
Vertex position	0.1	0.1	0.1	0.1
$C_{W/Z}$ theoretical uncertainty	0.6	0.6	0.6	0.3
Total experimental uncertainty	1.8	1.8	2.0	2.7
$A_{W/Z}$ theoretical uncertainty	1.5	1.7	2.0	2.0
Total excluding luminosity	2.3	2.4	2.8	3.3
Luminosity				3.4

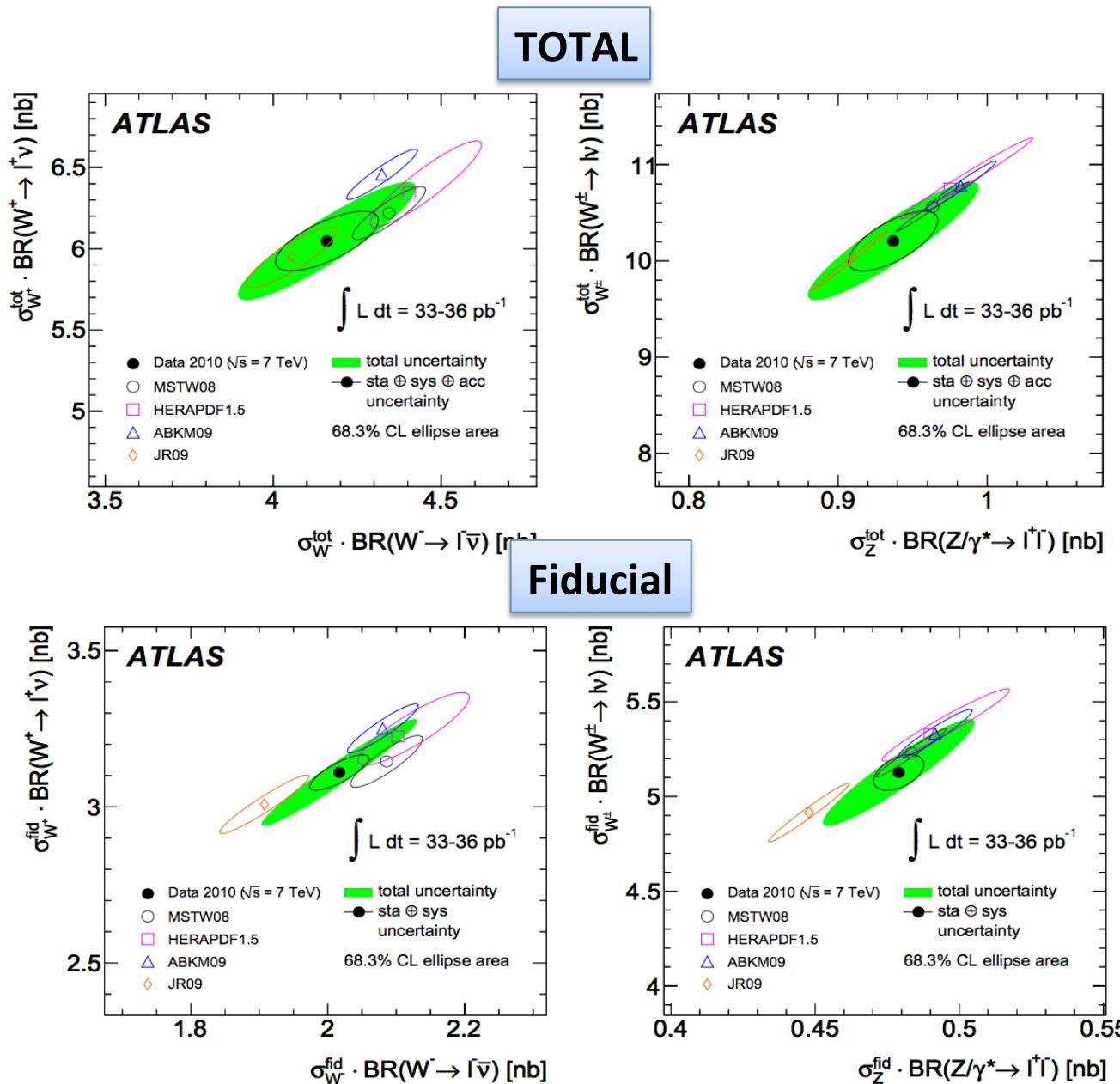
TABLE VI. Summary of relative systematic uncertainties on the measured integrated cross sections in the electron channels in per cent. The theoretical uncertainty of $A_{W/Z}$ applies only to the total cross section.

muon	$\delta\sigma_{W^\pm}$	$\delta\sigma_{W^+}$	$\delta\sigma_{W^-}$	$\delta\sigma_Z$
Muon reconstruction	0.5	0.5	0.5	0.1
Muon isolation	0.3	0.3	0.3	0.6
Muon p_T resolution	0.2	0.2	0.2	0.3
Muon p_T scale	0.04	0.03	0.05	0.02
QCD background	0.4	0.6	0.6	0.2
Electroweak+ $t\bar{t}$ background	0.6	0.5	0.8	0.3
E_T^{miss} resolution and scale	0.4	0.3	0.4	0.02
Pile-up modeling	0.5	0.4	0.6	—
Vertex position	0.3	0.3	0.3	0.3
$C_{W/Z}$ theoretical uncertainty	0.1	0.1	0.1	0.1
Total experimental uncertainty	0.8	0.8	0.7	0.3
$A_{W/Z}$ theoretical uncertainty	1.6	1.7	1.7	0.9
Total excluding luminosity	1.5	1.6	2.1	2.0
Luminosity	2.1	2.3	2.6	2.2

TABLE IX. Summary of relative systematic uncertainties on the measured integrated cross sections in the muon channels in per cent. The efficiency systematic uncertainties are partially correlated between the trigger, reconstruction and isolation terms. This is taken into account in the computation of the total uncertainty quoted in the table. The theoretical uncertainty on $A_{W/Z}$ applies only to the total cross section.

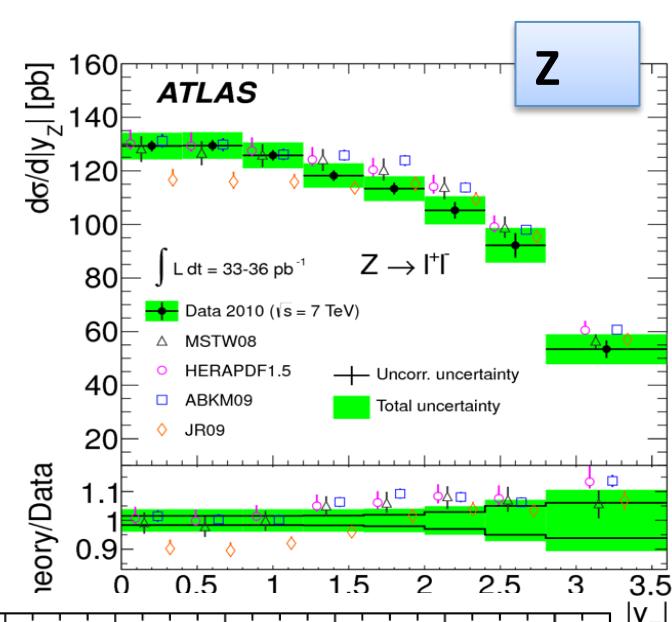
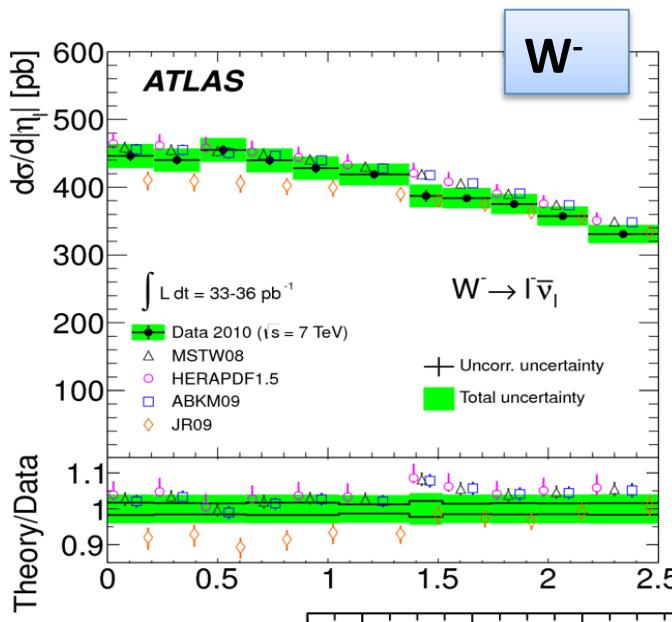
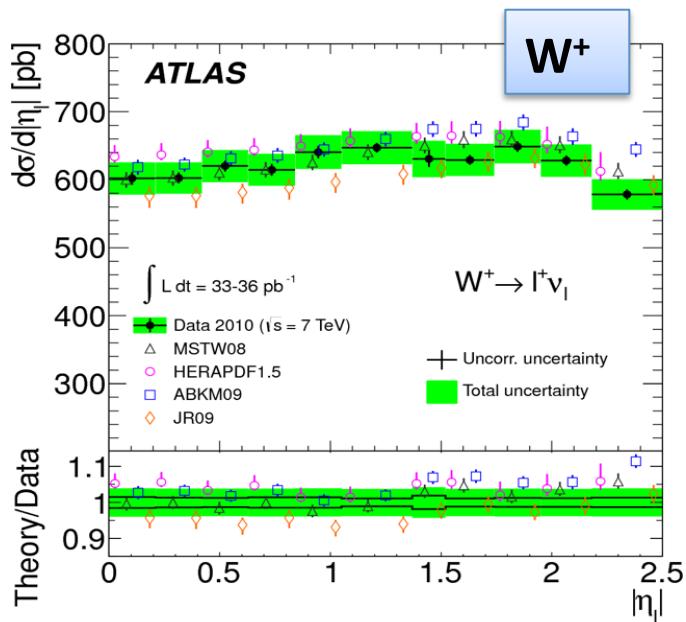
Total vs fiducial cross sections results

- Comparisons in the **common fiducial ($||\eta|<2.5$ and $y_z<3.6$, respectively) regions** disentangle theory and experimental effects better, i.e. employing fully the $\sim 1\%$ uncertainty for more detailed comparisons to PDFs, w/o the additional extrapolation uncertainty.
- Overall, NNLO QCD comparisons in remarkable agreement.**

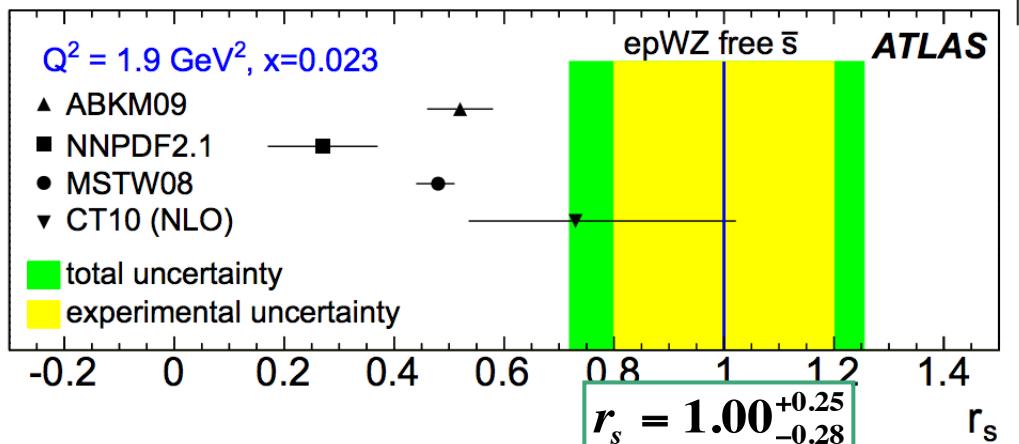


Comparisons with NNLO QCD & PDF fits

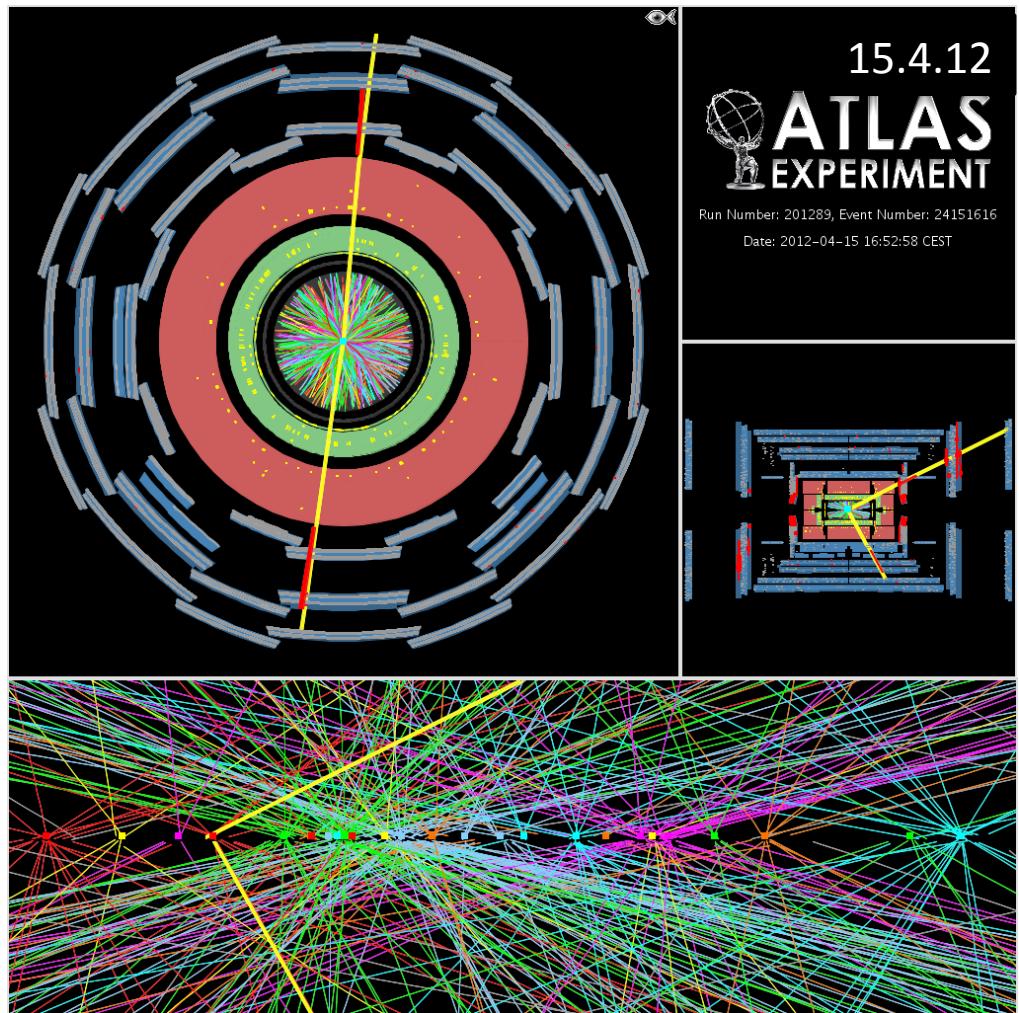
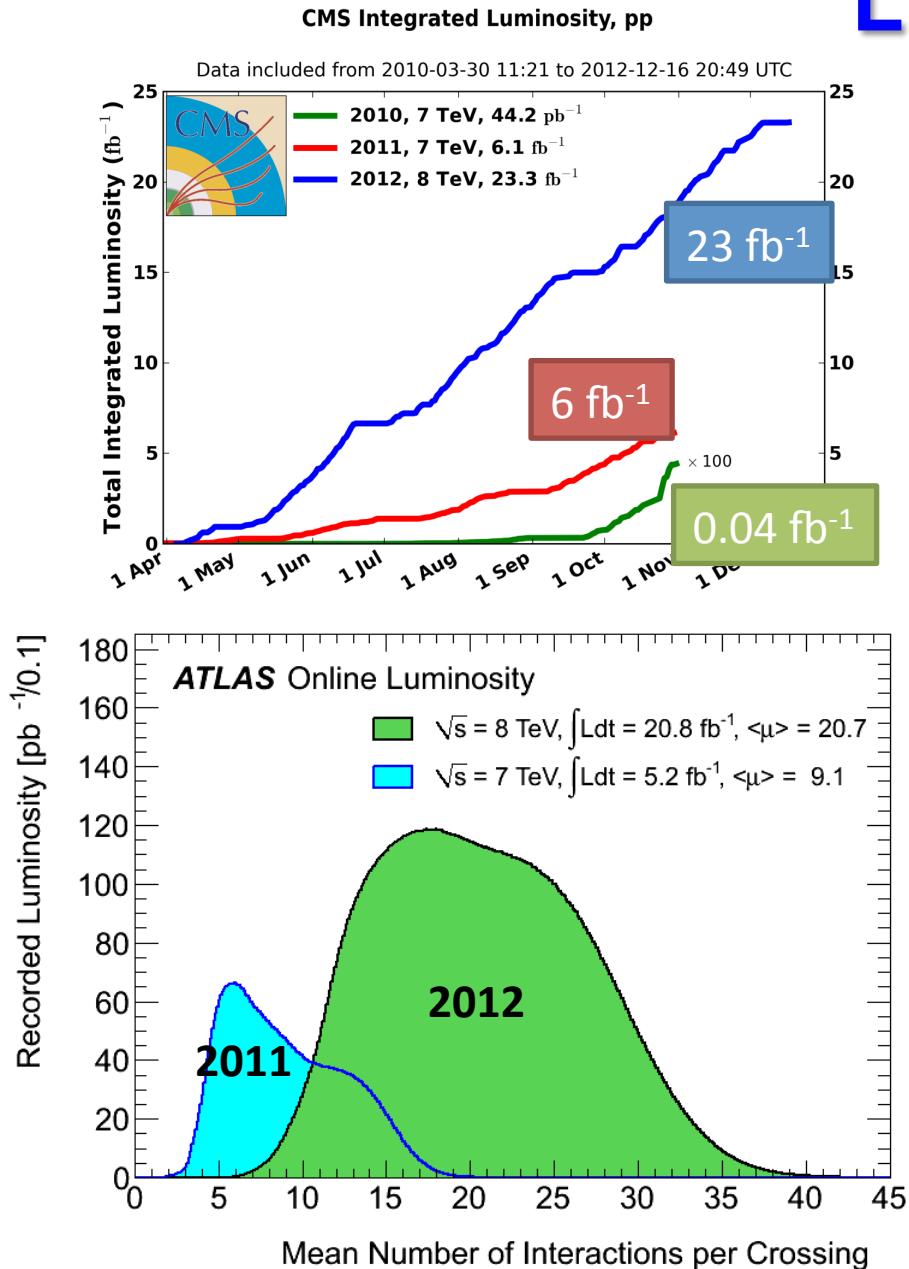
Combined measurements compared to NNLO QCD predictions:
 → more deviations apparent than e.g. in W charge asymmetry
 → larger potential to bring impact on PDFs



→ QCD fit of data [arXiv:1203.40511]
 in combination with HERA I data
 → 2% precision at 10000 GeV^2
 yields relative strange-to-antidown
 density at $x=0.013$ and $Q^2=1.9 \text{ GeV}^2$
 with an uncertainty of 25%



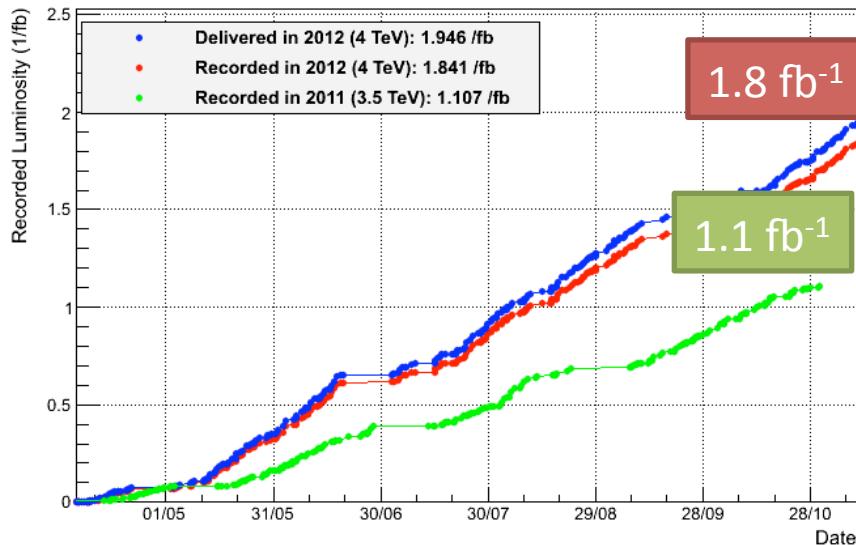
LHC data 2011 and 2012



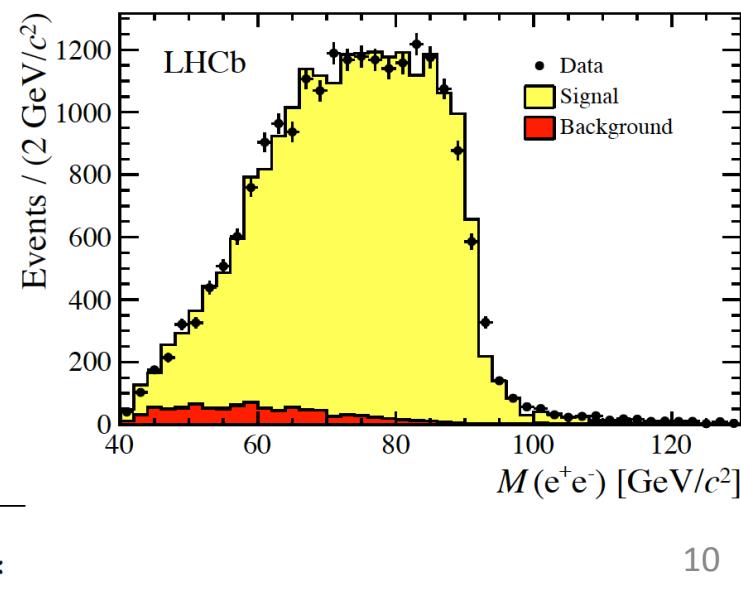
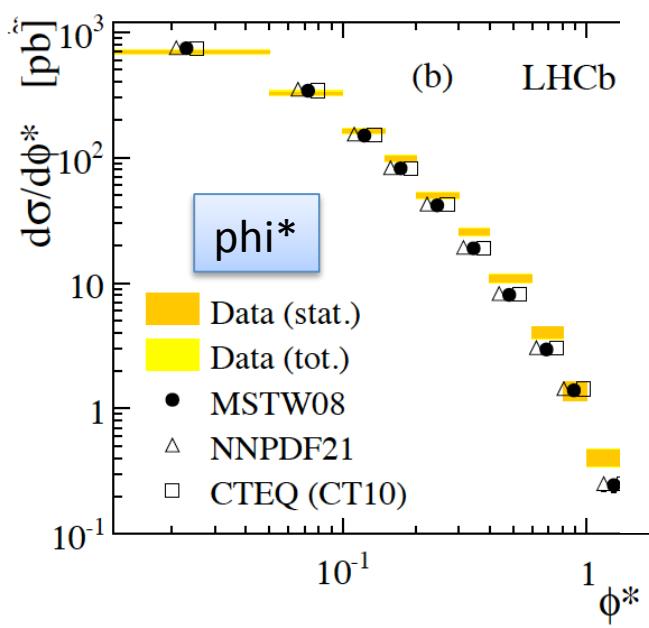
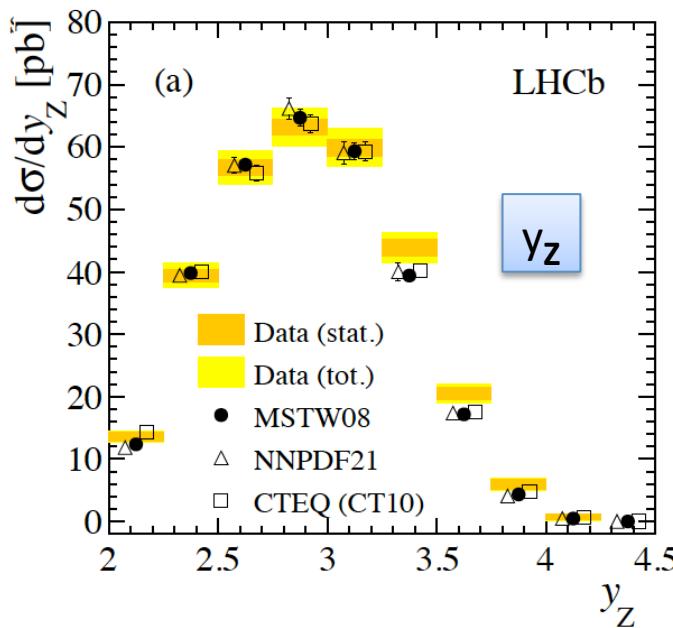
→ challenge for jets and missing ET → simulated in MC
 → ‘no’ issue for 2 high pT leptons,
 except trigger threshold for single lepton triggers

LHCb data in 2011 and 2012

LHCb Integrated Luminosity in 2011 and 2012



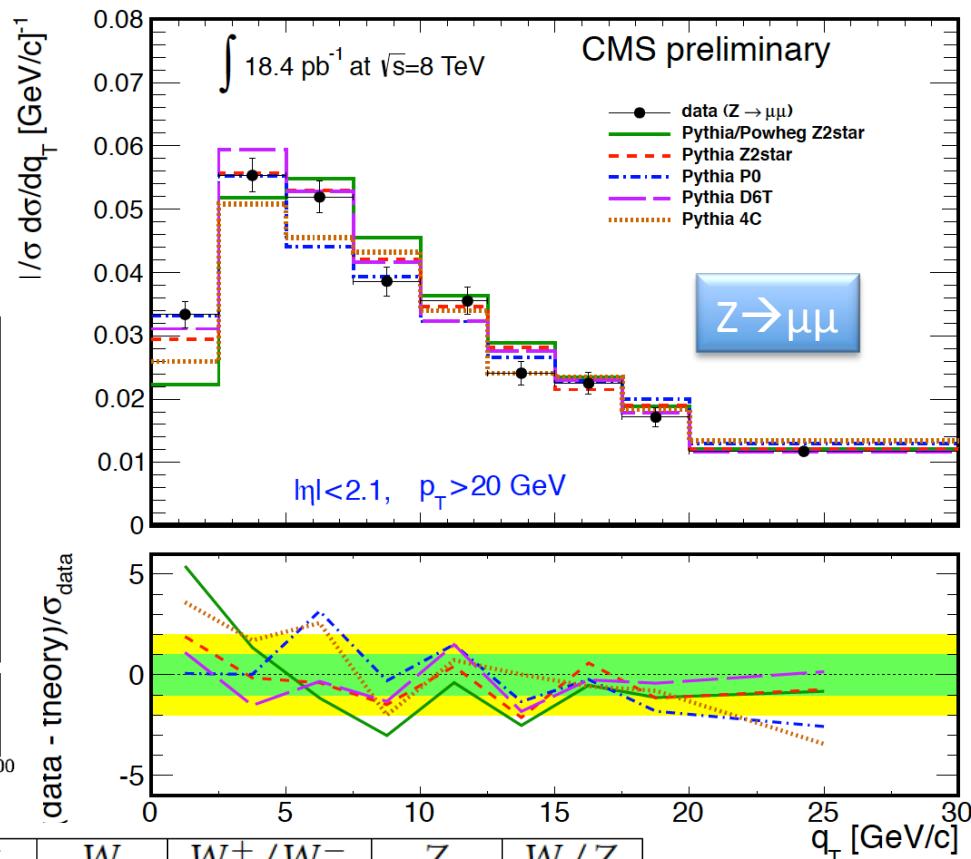
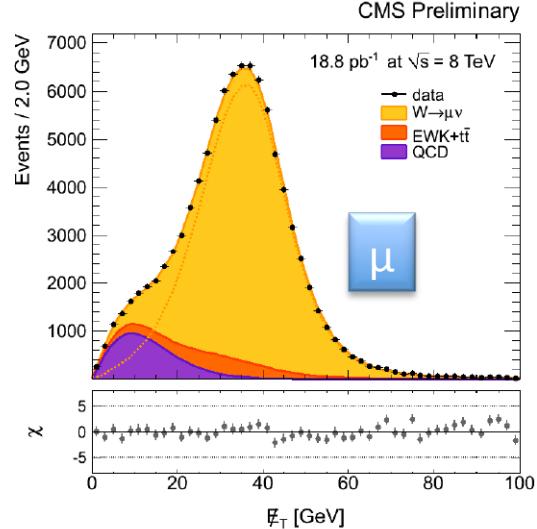
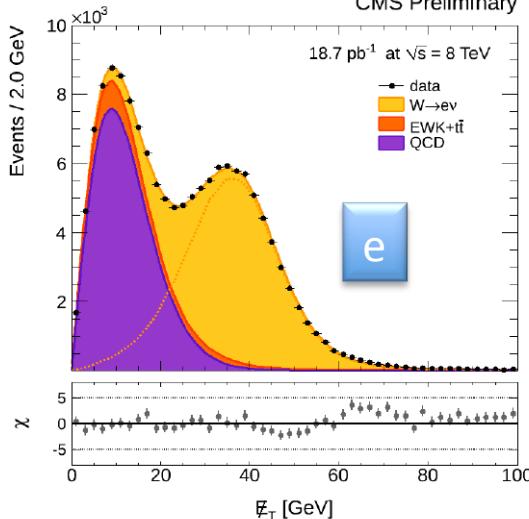
- 2011 data : $Z \rightarrow ee$, 60-120 GeV, $p_T > 20$ GeV, $2 < \eta < 4.5$ [0.94 fb⁻¹] : y_Z and ϕ^*
- dominated by luminosity systematics of ~3.5% [arXiv:1110.2866] → 2012 : 2% expected
- calorimeters optimised for low $p_T < 10$ GeV → E_T underestimated by 25% for $p_T > 10$ GeV
- normalised to data (bgd. subtracted) mass peak well simulated
- exp. syst. : 2.8% (1.9% trig, 1.6% track, 1.3% PID)



CMS W, Z @ 8 TeV

low pile-up 18.7 pb^{-1} ($\delta L = 4.4\%$)

Selected W candidates, fit of Etmiss spectra per channel, no M_T cut



Source	W^+	W^-	W	W^+/W^-	Z	W/Z
e Lepton reconstruction & identification	2.8%	2.5%	2.5%	3.8%	2.8%	3.8%
e Momentum scale & resolution	0.4%	0.7%	0.5%	0.3%	-	0.5%
e E_T^{miss} scale & resolution	0.8%	0.7%	0.8%	0.3%	-	0.8%
e Background subtraction / modeling	0.2%	0.3%	0.3%	0.1%	0.4%	0.5%
Total experimental	3.0%	2.7%	2.7%	3.8%	2.8%	3.9%
Theoretical uncertainty	2.1%	2.6%	2.7%	1.5%	2.6%	2.0%
Lumi	4.4%	4.4%	4.4%	-	4.4%	-
Total	5.7%	5.8%	5.8%	4.1%	5.8%	4.4%
μ Lepton reconstruction & identification	1.0%	0.9%	1.0%	1.2%	1.1%	1.5%

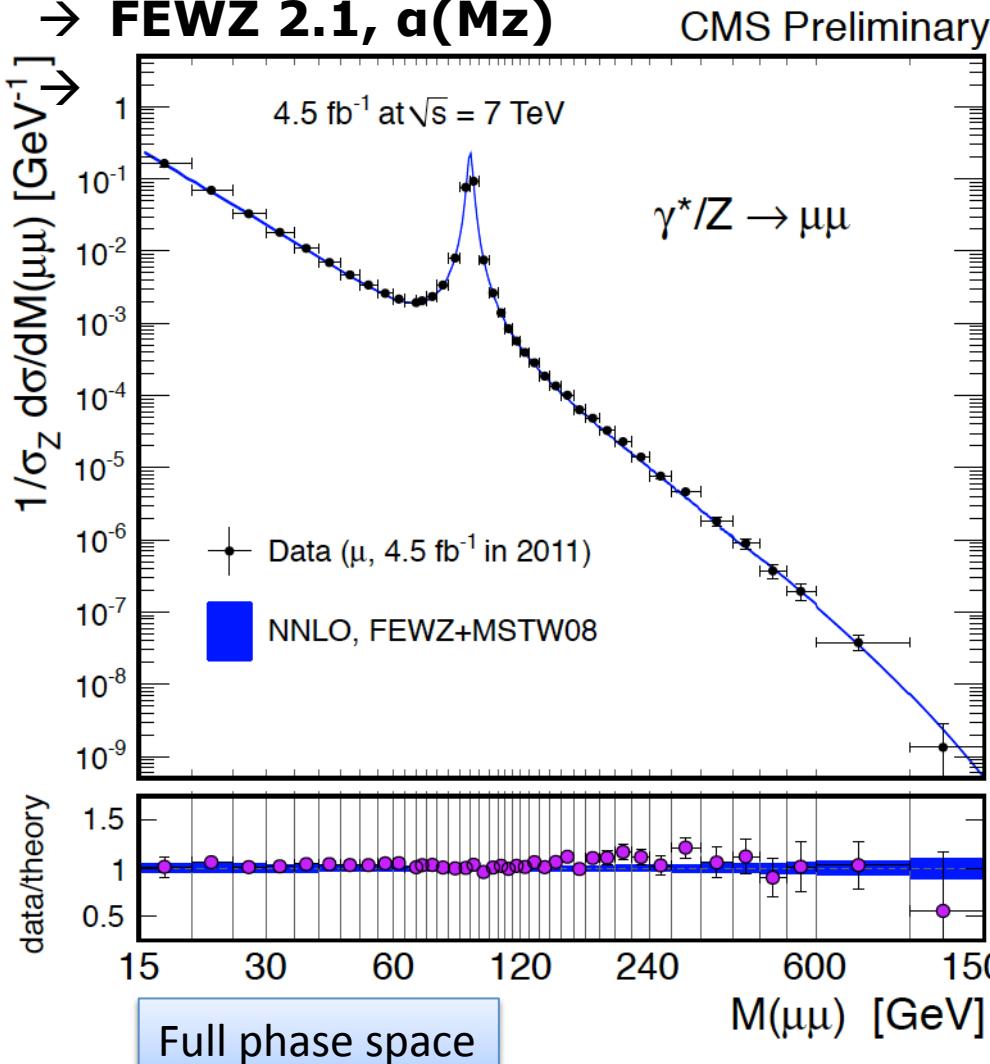
→ for
extrapolation
to total cross
section

NC DY mass spectrum @ 7 TeV

NC DY: CMS-PAS-EWK-11-007

→ e and mu channels, norm.

→ FEWZ 2.1, $\alpha(\text{Mz})$

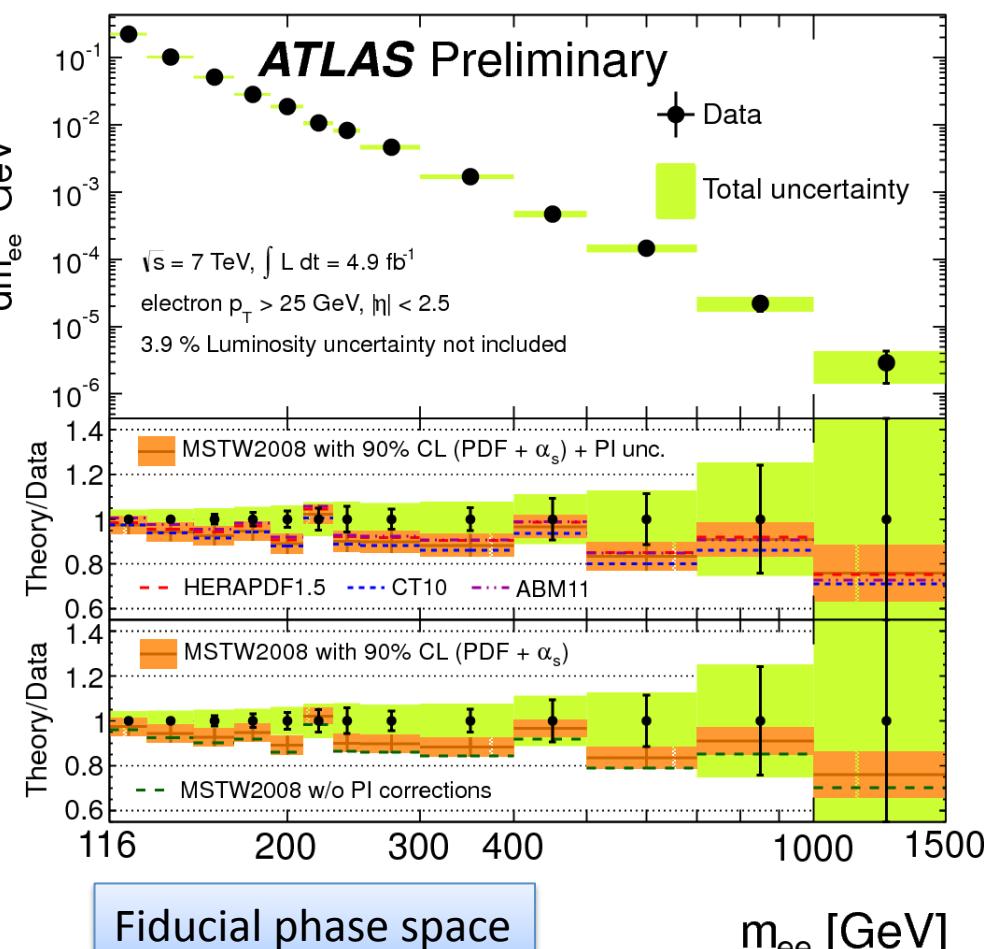


ATLAS-CONF-2012-159

→ only e channel, not norm.

→ FEWZ 3.1.b2 NNLO QCD +NLO

EW, Gμ , photon-induced bgd.



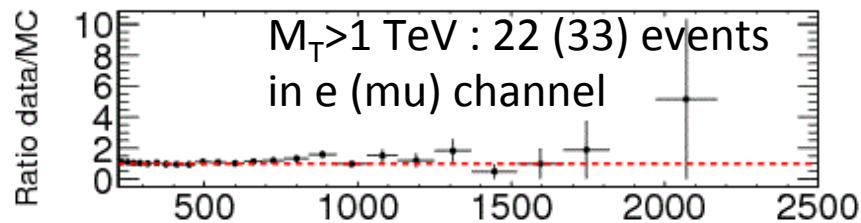
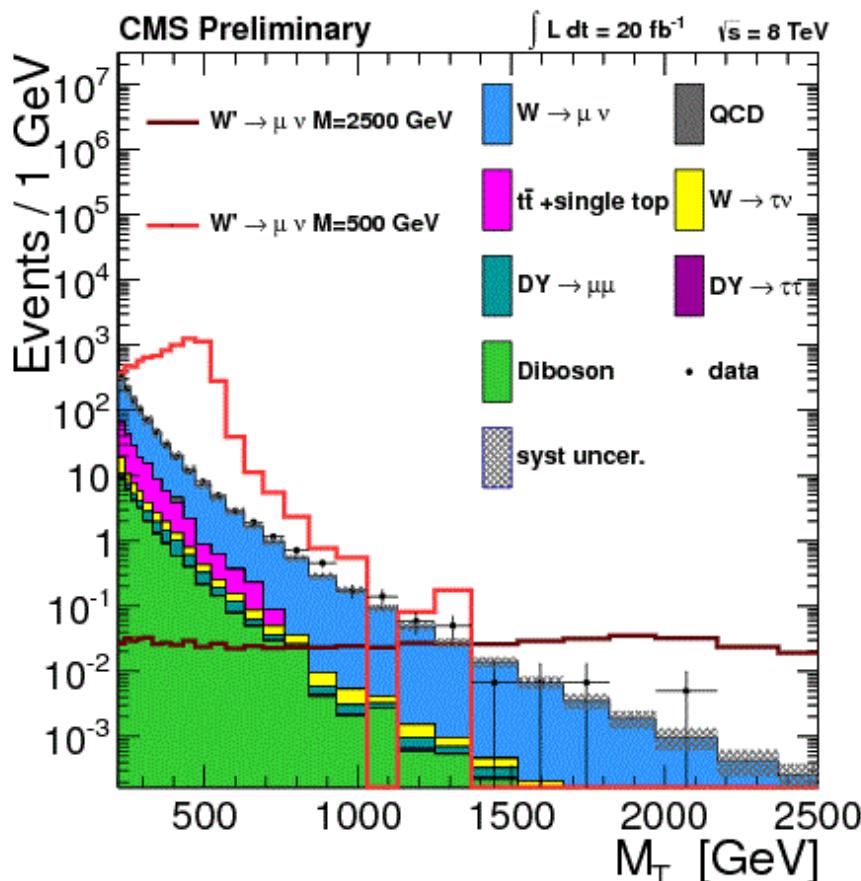
Systematics at high masses

Source of systematic uncertainty	Bin: 116-130 GeV [%]	Bin: 1000-1500 GeV [%]
Total background estimate	1.3	8.2
Electron reconstruction and identification	2.8	3.0
Electron energy scale and resolution	2.1	3.3
Unfolding method	1.5	1.5
Trigger efficiency	0.8	0.8
MC modelling	0.2	0.3
MC statistics	0.7	0.4
Total experimental uncertainty	4.2	9.8
Luminosity uncertainty	3.9	3.9
Theoretical C_{DY}	0.1	0.3
Theoretical $C_{\text{DY}}/E_{\text{DY}}$	0.3	0.4
statistical uncertainty	1.1%	50%

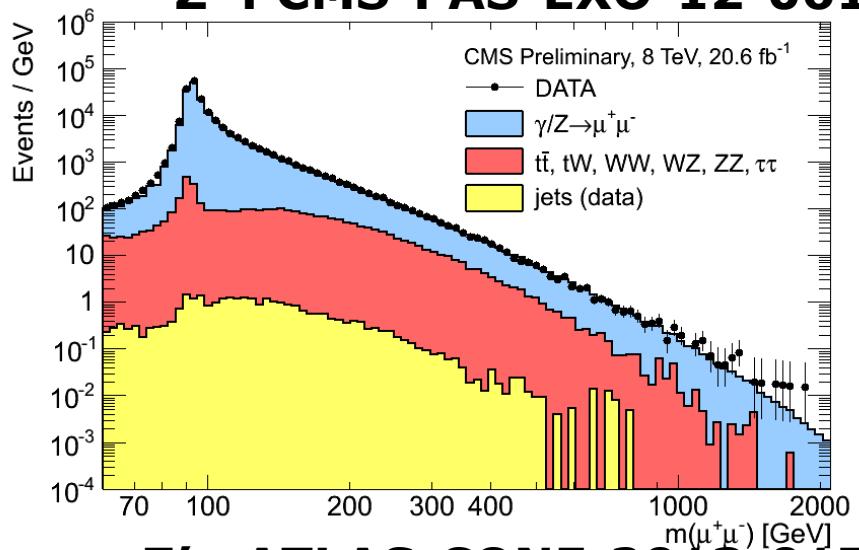
- statistics dominated for high masses : for 100 fb^{-1} we may expect 5% stats. and 5% syst. error
- background description may improve over time : challenge : measurement and modelling of non-resonant photon induced dilepton production and diboson production for $\text{WZ} \rightarrow \text{ll} + \text{anything}$ and $\text{ZZ} \rightarrow \text{ll} + \text{anything}$ (and W or Z could be off-shell)

Towards 8 TeV DY ... via searches first!

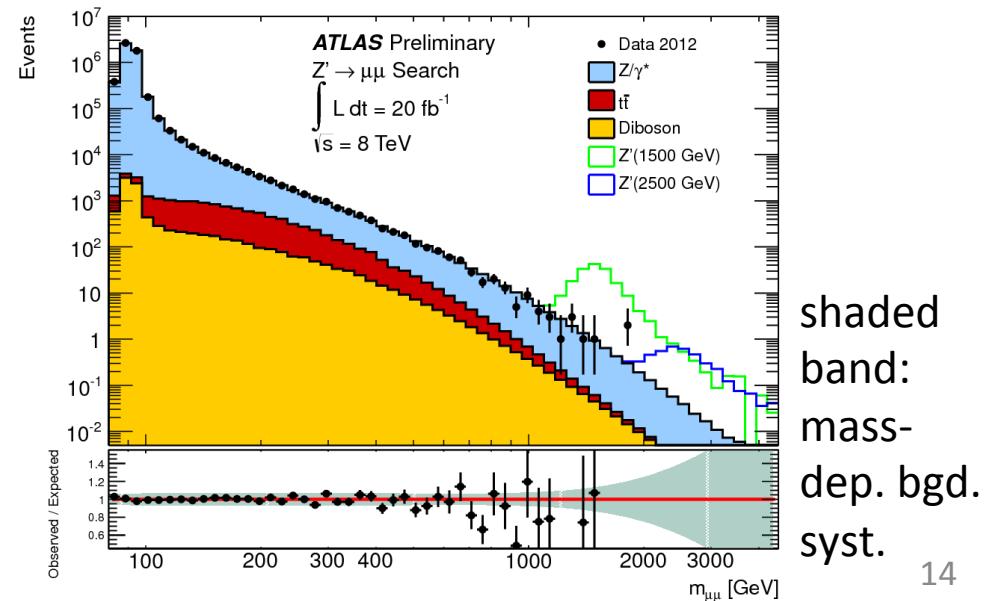
W': CMS-PAS-EXO-12-060



Z' : CMS-PAS-EXO-12-061



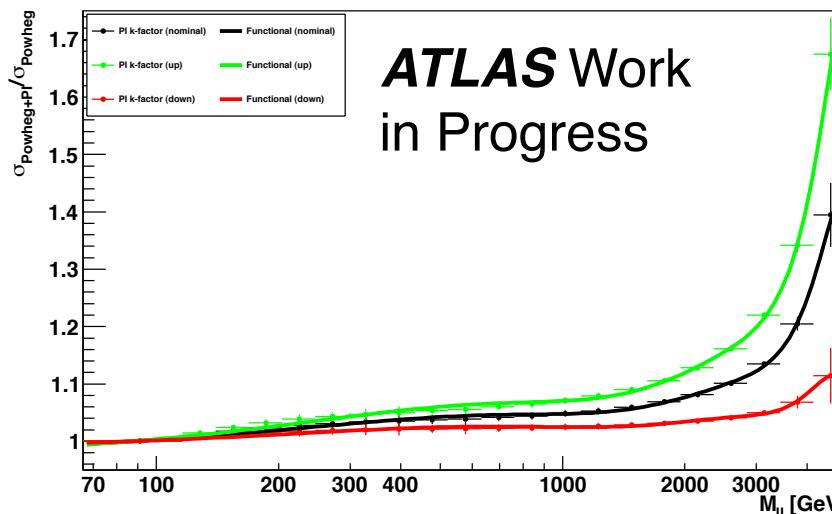
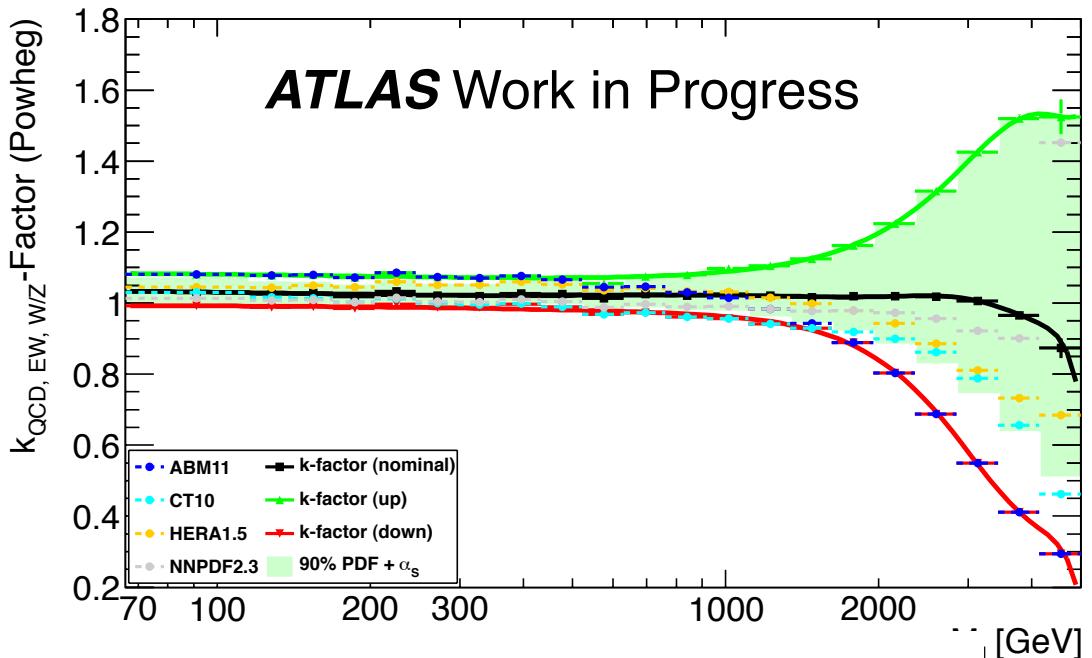
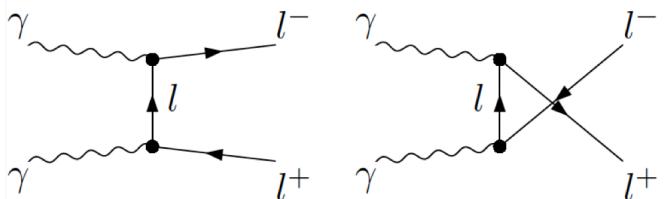
Z' : ATLAS-CONF-2013-017



“k-factors” and photon-induced contributions

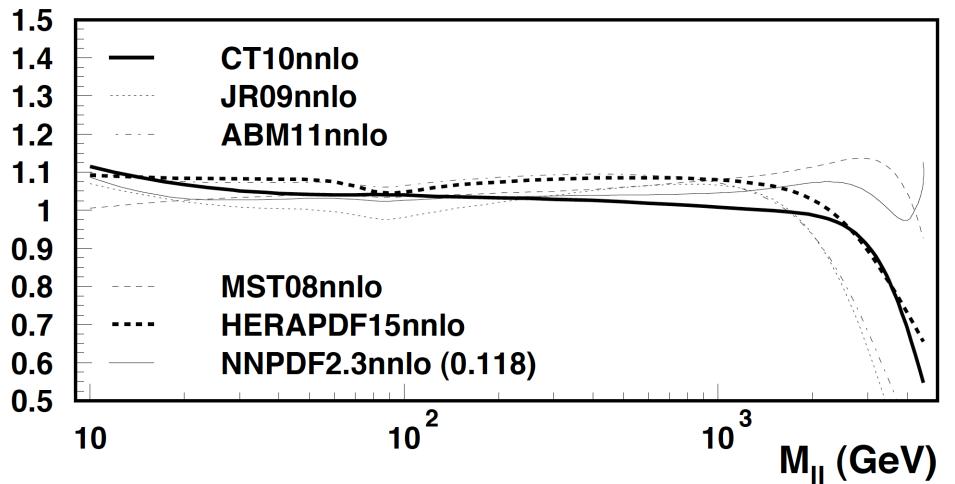
ATLAS-CONF-2013-017
related work

- novel method of “k-factors”: NNLO QCD + NLO EW + real W,Z radiation “k-factor” w.r.t. nominal ATLAS NC DY Powheg MC
- photon-induced contribution w.r.t. nominal “k-factor” reweighted NC DY MC estimated using updated MRST200qed grid (R.Thorne private comm.) with fid. lepton cuts

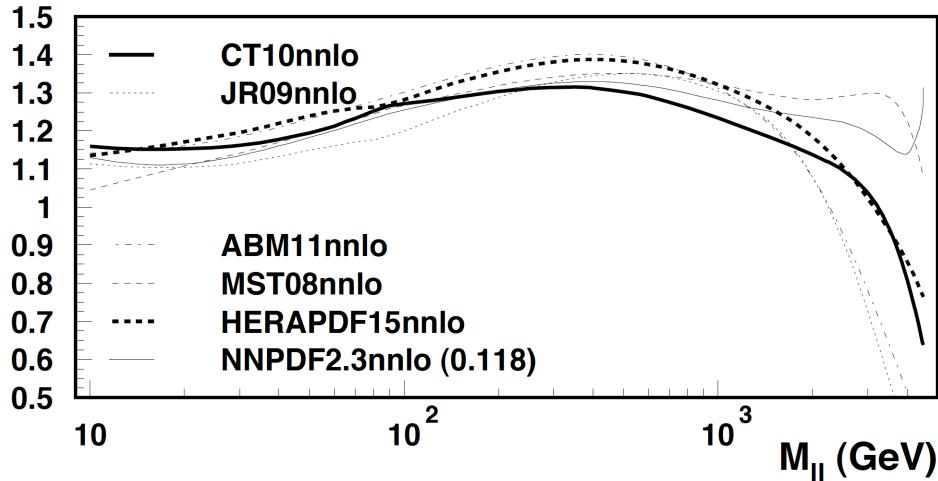


NNLO/NLO and NNLO/LO k-factors

NC DY @ 8 TeV

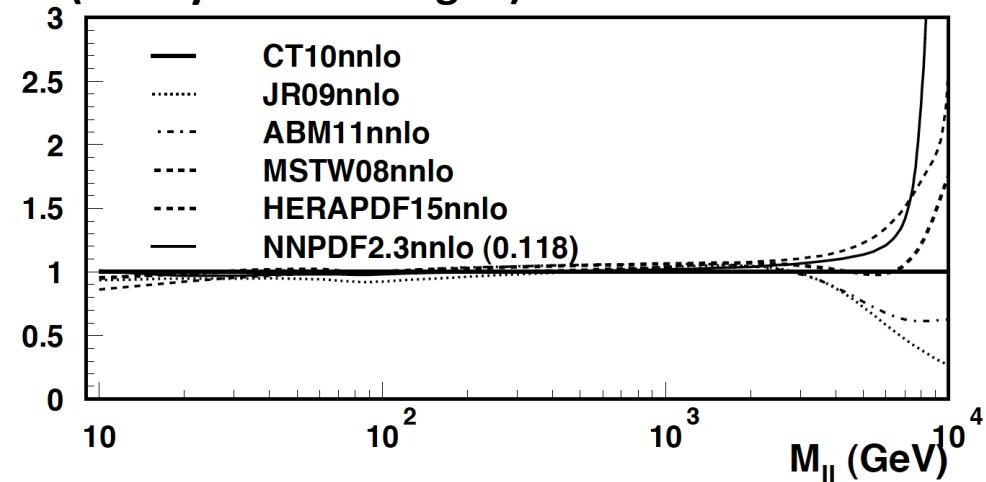


NNLO PDF/MSTW LO



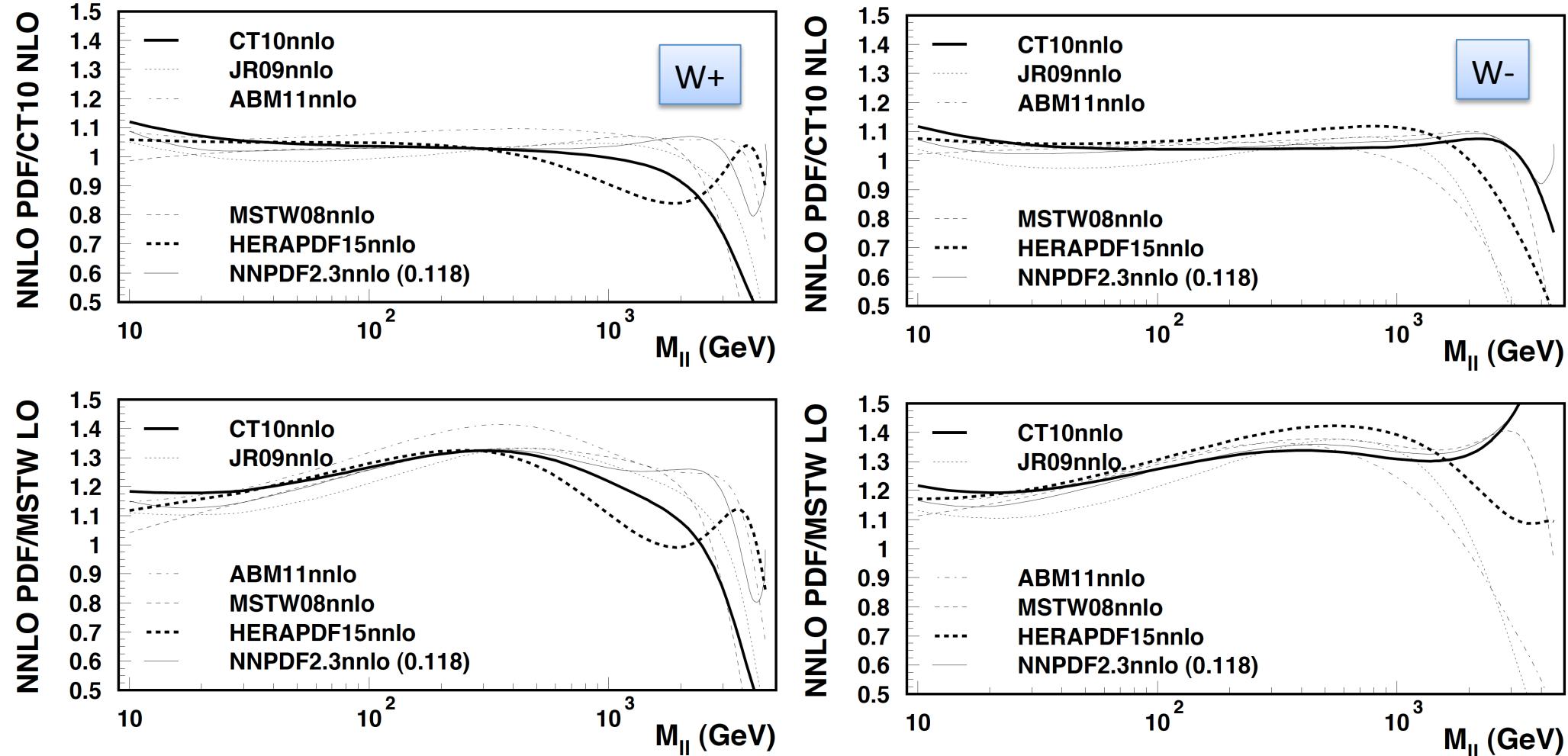
NC DY @ 14 TeV

→ wide spread in predictions for NNLO NC DY cross sections at high masses
(note y-scale enlarged)



VRAP0.9 used for calculations of k-factors and scale uncertainties

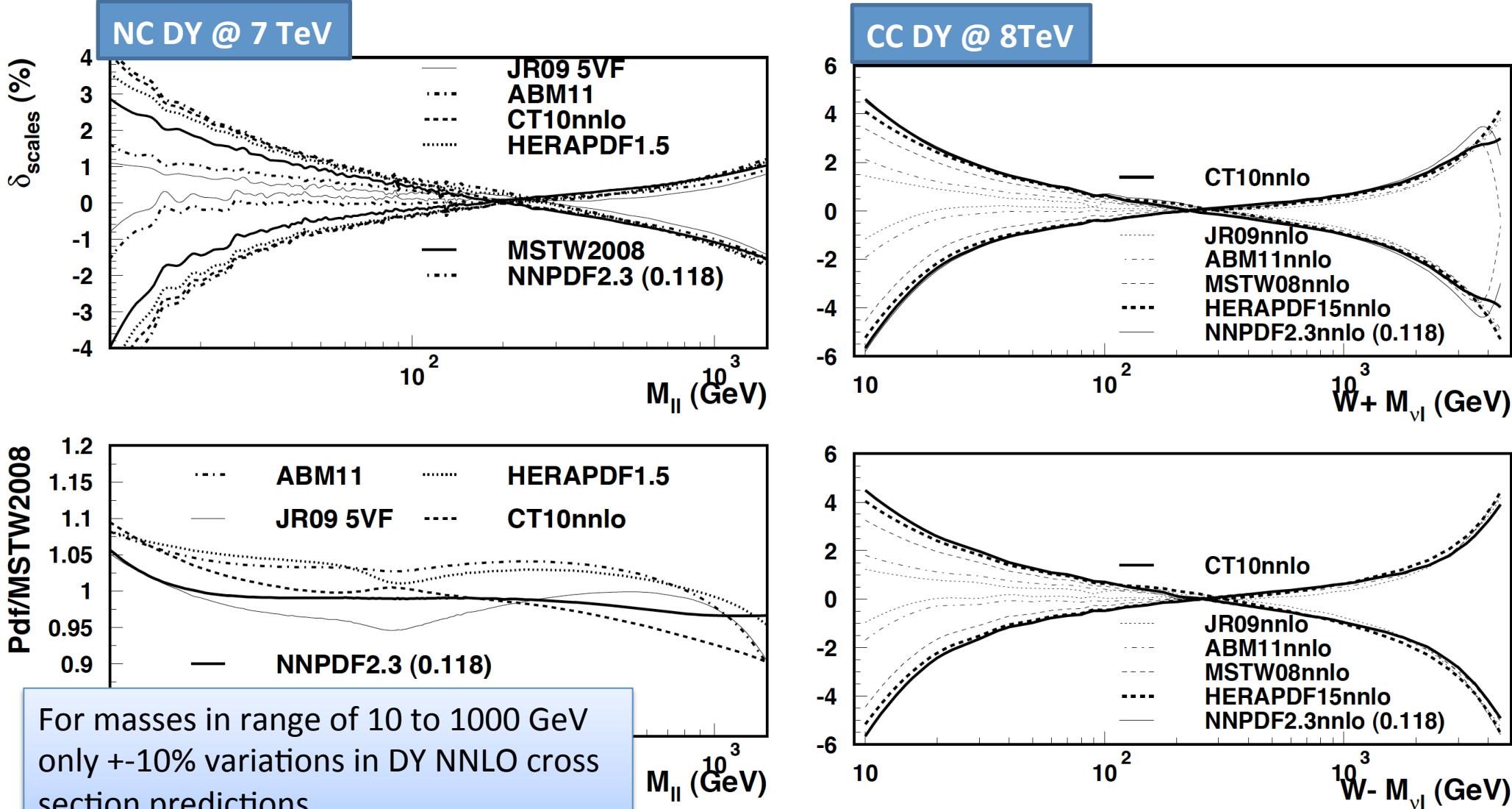
... and examples for CC DY @ 8 TeV



→ NNLO/NLO k-factors usually in range of 0.9 to 1.1 (moderate),
but strong deviations for $M > 1$ TeV

Scale uncertainties at NNLO

- Using VRAP v0.9 to calculate scale uncertainties $2^*\mu_{R,F}$ and $\frac{1}{2}^*\mu_{R,F}$
- Estimate of NNLO scale uncertainties sensitive to PDF choice and invariant mass range



What may we have with 100 fb⁻¹ ...

- ✓ We may anticipate for 100 fb⁻¹ NC and CC DY data over a wide kinematic range of 60 to 1500 GeV with negligible stat. precision (well <0.1%) around the peak region up to 5% at M~ 1 TeV while the systematic uncertainties are expected to be ½ of the present systematic uncertainties, e.g. for NC DY in the range of 0.5% at the peak up to 5% at high masses
- exploring more and more fully the data driven background estimates and the tag and probe based efficiency calculations (significant reduction of stats. component of the systematic uncertainty).

However, with increased statistics, and such small level of systematic uncertainties there may be also NEW effects at the sub-percent level 'discovered'.

Crucial ingredients ...

- ❖ Reduction of the luminosity uncertainties which is already for the 2011 GPD data 1.8%, and similar values are expected for the 2012, i.e. about 2%; 'worst case' would be the VdM scan based uncertainties of 3-4%
- ❖ Improved modelling of DY at NLO, e.g Powheg + EW for NC and CC DY, and improved modelling of significant irreducible backgrounds, e.g. diboson production at NLO for $WZ \rightarrow ll + \text{anything}$ and $ZZ \rightarrow ll + \text{anything}$
- ❖ High statistics MC simulations, also with alternative PS, UE and ME to estimate systematic uncertainties → Question : How to quantify correlations among various experiments due to MC (ME, PS, UE) and theory?
- ❖ Publication of data with correlations, for normalised and absolute cross section results → this may allow the best comparison of experimental results

A wish list for discussion & studies

.. some tasks are already under study also in LPCC and EW experimental and theory WG's

- ❖ Numerical stability of NNLO and NLO calculations, e.g. issues related to choice of symmetric p_T cuts, intrinsic integration settings, and the case of fine bins and high precision (\rightarrow smaller than exp. uncertainties, so $<0.5\%$ per bin), etc.
- “optimal” choice (and documentation) of EW parameters and SM inputs
- high precision ($<0.1\%$ per bin) “APPLgrids at NNLO” ...?
- ❖ Precision evaluation of missing HO EW (ISR, interferences, weak) corrections and QED FSR modelling; application of missing HO EW corrections and remaining systematics
- ❖ Uncertainties due to further missing HO QCD effects as usually estimated by “scale uncertainties” \rightarrow realistic prescription for NNLO (CPU time!)
- ❖ Improved modelling of $p_T(W,Z)$: implementation of resummation into NLO MC models (but e.g. also control of resummation scale)
- ❖ Improved modelling and measurement proposals for non-resonant photon-induced dilepton productions, but also for the NLO gamma-p induced dilepton and W productions
- ❖ Improved modelling of real W and Z radiation beyond LO approach outlined by U.Baur, arXiv:hep-ph/0611241